OVERVIEW OF THE NATIONAL TASK FORCE REPORT ON HIGH ENERGY DENSITY PHYSICS

Presented by
Ronald C. Davidson

Presented to
Board on Physics and Astronomy

November 6, 2004

KEY BACKGROUND REFERENCES FOR TASK FORCE DELIBERATIONS

HEDP Task Force

1. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003);

2. *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003);

3. *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* (Report on the SAUUL Workshop, June 17-19, 2002); and

4. Pertinent technical reviews and federal advisory committee reports.

TASK FORCE CHARGE AND APPROACH

HEDP Task Force

In response to the January 13, 2004, charge letter from Joe Dehmer on behalf of the Interagency Working Group on the Physics of the Universe, the HEDP Task Force addressed the following key charge areas in order to identify the major components of a national high energy density physics program:

1. Identify the principal research thrust areas of high intellectual value that define the field of high energy density physics;

2. For each of the thrust areas, identify the primary scientific questions of high intellectual value that motivate the research;

TASK FORCE CHARGE AND APPROACH

HEDP Task Force

3. Develop the compelling scientific objectives and milestones that describe what the federal investment in high energy density physics are expected to accomplish;

4. For each principal thrust area, identify the frontier research facilities and infrastructure required to make effective progress; and

5. Identify opportunities for interagency coordination in high energy density physics.

HEDP TASK FORCE MEMBERSHIP

Ronald C. Davidson, Chair, Princeton University
Tom Katsouleas, Vice-Chair, University of Southern California
Jonathan Arons, University of California at Berkeley
Matthew Baring, Rice University
Chris Deeney, Sandia National Laboratories
Louis DiMauro, Ohio State University
Todd Ditmire, University of Texas, Austin
Roger Falcone, University of California, Berkeley
David Hammer, Cornell University
Wendell Hill, University of Maryland, College Park
Barbara Jacak, State University of New York, Stony Brook
Chan Joshi, University of California, Los Angeles

HEDP TASK FORCE MEMBERSHIP

Fred Lamb, University of Illinois, Urbana
Richard Lee, Lawrence Livermore National Laboratory
B. Grant Logan, Lawrence Berkeley National Laboratory
Adrian Mellisinos, University of Rochester
David Meyerhofer, University of Rochester
Warren Mori, University of California, Los Angeles
Margaret Murnane, University of Colorado, Boulder
Bruce Remington, Lawrence Livermore National Laboratory
Robert Rosner, University of Chicago

HEDP TASK FORCE MEMBERSHIP

Dieter Schneider, Lawrence Livermore National Laboratory
Isaac Silvera, Harvard University
James Stone, Princeton University
Bernard Wilde, Los Alamos National Laboratory
William Zajc, Columbia University
Ronald McKnight, Secretary, Gaithersburg, Maryland

TASK FORCE WORKING GROUPS

HEDP Task Force

A - HEDP in Astrophysical Systems
Rosner (Chair), Arons, Baring, Lamb, Stone

B - Beam-Induced HEDP (RHIC, heavy ion fusion, high-intensity accelerators, etc.) Joshi (Chair), Jacak, Logan, Mellisinos, Zajc

S - HEDP in Stockpile Stewardship Facilities (Omega, Z, National Ignition Facility, etc.) Remington (Chair), Deeney, Hammer, Lee, Meyerhofer, Schneider, Silvera, Wilde

U - Ultrafast, Ultraintense Laser Science
Ditmire (Chair), DiMauro, Falcone, Hill, Mori, Murnane

HEDP TASK FORCE REPORT OUTLINE

HEDP Task Force

Preface

1. Introduction and Report Outline
2. High Energy Density Physics in Astrophysical Systems
3. Beam – Induced High Energy Density Physics
4. High Energy Density Physics in Stockpile Stewardship Facilities
5. Ultrafast Ultraintense Laser Science

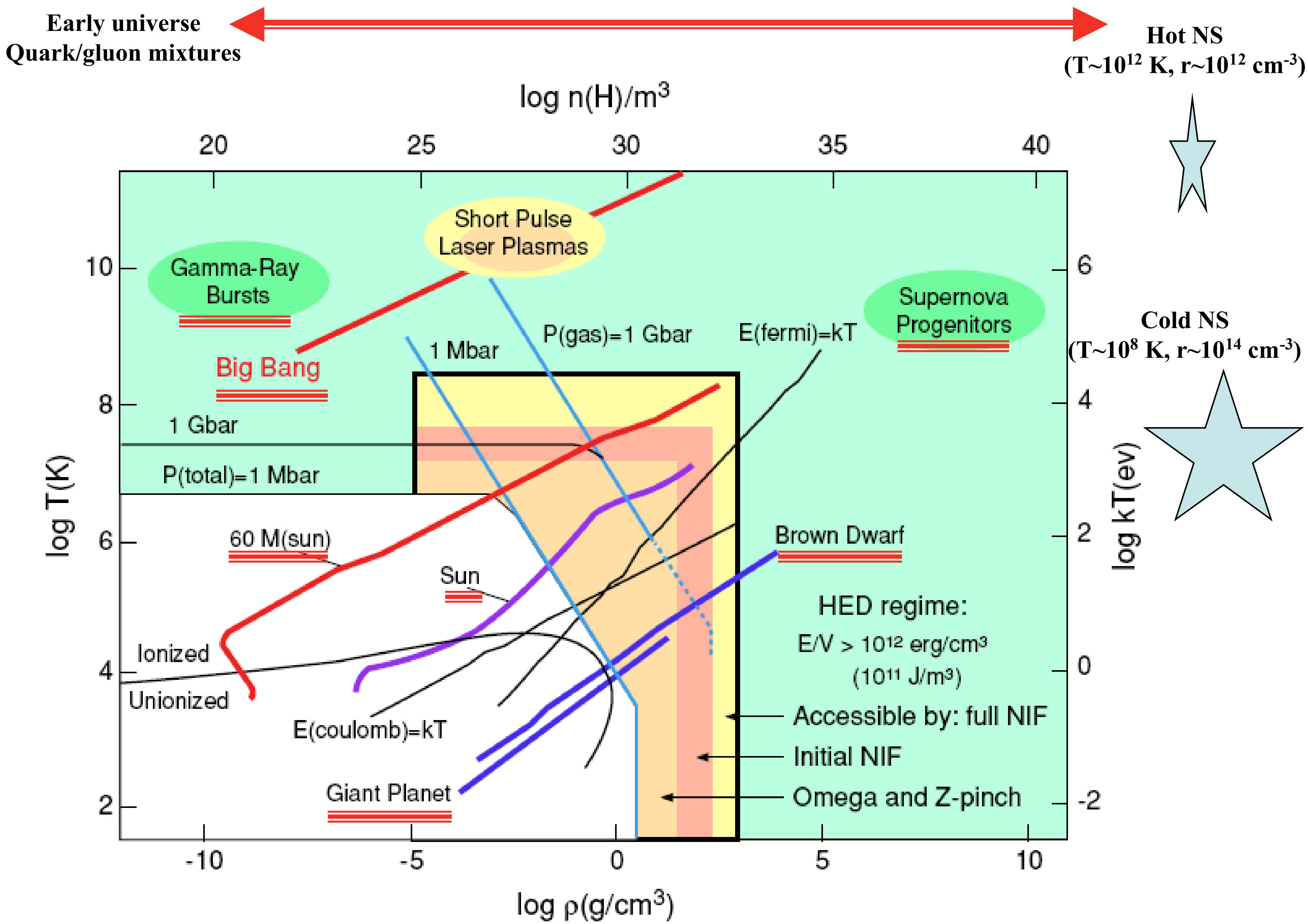
***Appendix A* – Charge to the High Energy Density Physics Task Force**
***Appendix B* - Workshop Agenda**

Equivalent Parameters for High Energy Density (10^{11} J/m^3)

HEDP Task Force

Energy Density Parameter Corresponding to ~10^{11} J/m^3	**Value**
Pressure	1 Mbar
Electromagneic Radiation	
Electromagnetic wave (laser) intensity (I), (p ~I)	3 x 10^{15} W/cm^2
Blackbody radiation temperature (T_r), (p ~$T_r^{1/4}$)	5 x 10^6 K (400 eV)
Electric field strength (E), (p ~ E^2)	1.5 x 10^{11} V/m
Magnetic field strength (B), (p ~ B^2)	5 x 10^2 T
Particle Beams	
Current density for a beam of 30 GeV electrons	100 kA/cm^2
Current density for a beam of 10 MeV ions (m = 10m_{proton}, Z = 1)	4 MA/cm^2
Plasma Pressure	
Plasma density (n) for a thermal temperature (T) of 1 keV (10^7K), (p ~nT)	6 x 10^{20} cm^{-3}
Plasma density for energy / particle (temperature) of 1 GeV (10^{13}K), (p ~ nT)	6 x 10^{14} cm^{-3}
Ablation pressure	
Laser intensity (I) at 1 μm wavelength (λ), (p ~ $(I/\lambda)^{2/3}$)	4 x 10^{12} W/cm^2
Blackbody radiation temperature (T_r), (p ~ $T_r^{3.5}$)	9 x 10^5 K (75 eV)

Map of the High Energy Density Physics Universe



THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #1 - Astrophysical phenomena

What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

Thrust Area #2 - Fundamental physics of high energy density astrophysical phenomena

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

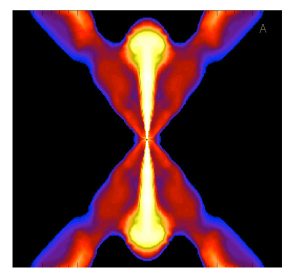
HEDP Task Force

Thrust Area #3 - Laboratory astrophysics

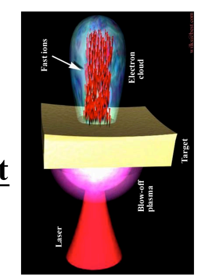
What are the limits to our ability to test astrophysical model and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

The “big questions” for HED astrophysics

- *How does matter behave under conditions of extreme temperature, pressure and density*?
  - Origin and evolution of giant planets and brown dwarfs.
  - Equation-of-state, opacities, conductivity, diffusivity, viscosity, … , of stellar matter.
  - Basic physics of degenerate plasmas (e.g., convection, URCA, …).
  - Nuclear burning: ignition? transition from flame to detonation?
  - Quark-gluon plasmas: the very early universe, strongly coupled plasmas.
  - Ultrahigh energy cosmic rays: origins? composition? propagation?
  - …
- *How does matter interact with photons and neutrinos under extreme conditions*?
  - Accreting black holes/neutron stars: disks, jets, …
  - Gamma ray bursters (GRBs).
  - Pair plasmas.
  - …



GRB model (Woosley & MacFadyen 1999)



Proposed GRB experiment
Liang & Wilkes 1998;
Wilkes et al. 2001)

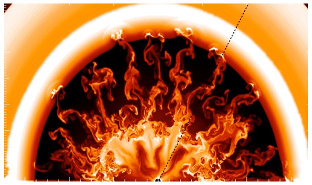
The three astrophysics thrust areas

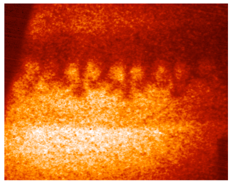
- Astrophysical phenomena: <u>Modeling</u>
  - The use of existing physics theory (or extrapolations of existing theory) to build models describing particular phenomena: "astroengineering"
- Astrophysical basic theory: <u>Fundamental physics</u>
  - Studies of the fundamental physical processes governing matter and radiation under high energy density conditions
- Astrophysical laboratory studies of high energy density
  - Measurement of fundamental material properties
  - Exploration of astrophysical phenomenology under controlled lab conditions, to build intuition
  - Direct connections to astrophysical phenomena via scaling
  - Validation of instruments, diagnostics, simulations …

Laboratory astrophysics

- Motivating question:
  - What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory; and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems as yet inaccessible to either theory or simulations?
- The four key science objectives
  - Measuring material properties at high energy densities: equations of state, opacities, …
  - Building intuition for highly nonlinear astronomical phenomena, but under controlled lab conditions (with very different dimensionless parameters): radiation hydrodynamics, magnetohydrodynamics, particle acceleration, …
  - Connecting laboratory phenomena/physics directly to astrophysical phenomena/physics (viz., in asymptotic regimes for Re, Rm, …): late-time development of Type Ia and II supernovae, …
  - Validating instrumentation, diagnostics, simulation codes, … , aimed at astronomical observations/phenomena

Type II SN shock simulation (Kifonidis et al. 2000)





Type II SN shock experiment (Robey et al. 2001)

Resource needs: the specifics of funding

- Forefront observational tools from ground and space
  - ‘Road map’ in place: NAS/NRC decadal “Survey of Astronomy and Astrophysics” and NAS/NRC report “Connecting Quarks with the Cosmos”
  - Road map cuts broadly across federal agencies: NASA, NSF, DOE/SC
- Critical mass activities in building new tools for simulations and experiments: new incremental funding for Centers
  - Successes of NSF Physics Frontier Centers and DOE/NNSA ASC/Alliances program allows scaling of likely level of critical-mass efforts in this area:
    - New generation large simulation codes will require both Center-level funding and large-scale access to forefront computing hardware
  - Level of funding/Center at least $2.5M/year, for periods of 5-10 years; of order 3-4 Centers in simulations and experimental activities: **$7.5-10M/yr**
- Developing and maintaining the necessary human ‘capital’
  - Centers are not enough, especially in experimental and theory/modeling
  - Steady-state ‘small grants’ program, at a level of 40 investigators (@$200K/annum): **~ $8M/yr**

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY PHYSICS

HEDP Task Force

Thrust Area #4 - Heavy-ion-driven high energy density physics and fusion

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Thrust Area #5 - High energy density science with ultrarelativistic electron beams

How can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY PHYSICS

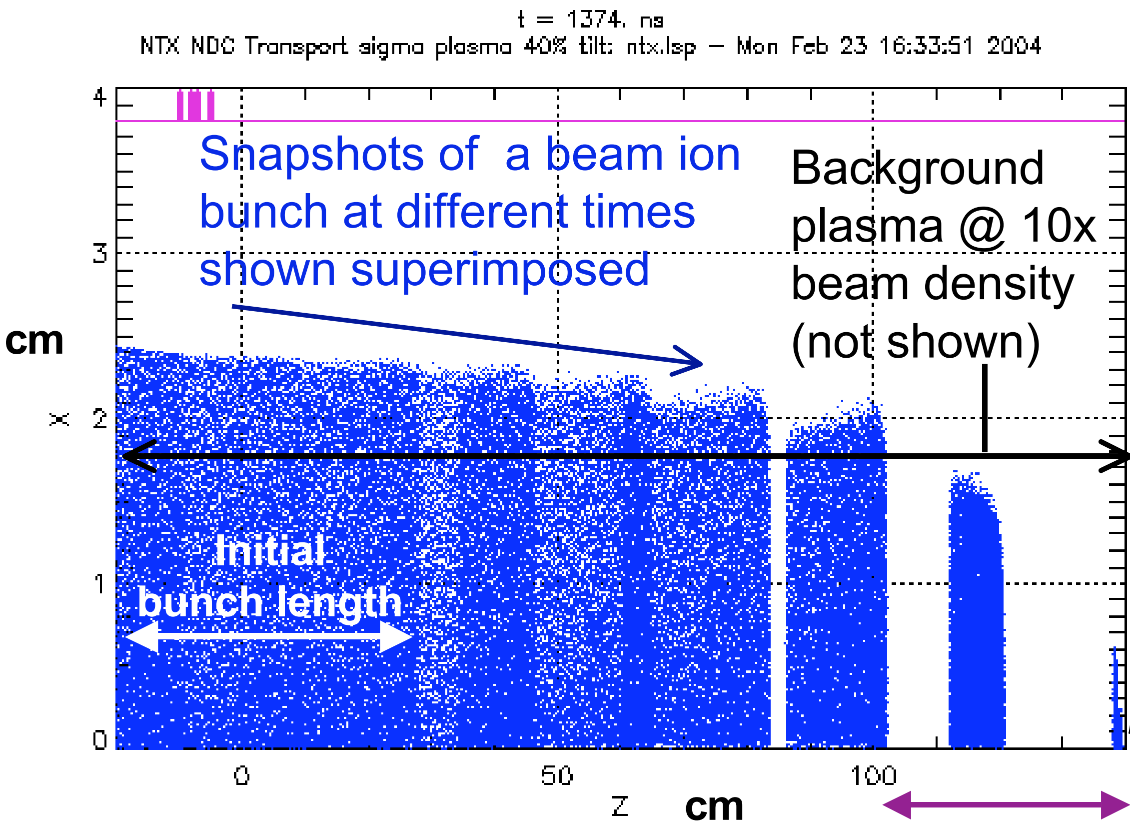
HEDP Task Force

Thrust Area #6 - Characterization of quark - gluon plasmas

What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?

Does the Quark Gluon plasma exhibit any of the properties of a classical plasma?

Simulations show large compressions of tailored-velocity ion beams



←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

•Axial compression 120 X

•Radial compression to 1/e focal spot radius < 1 mm

•*Beam intensity on target increases by 50,000 X*.

Existing 3.9T solenoid focuses beam

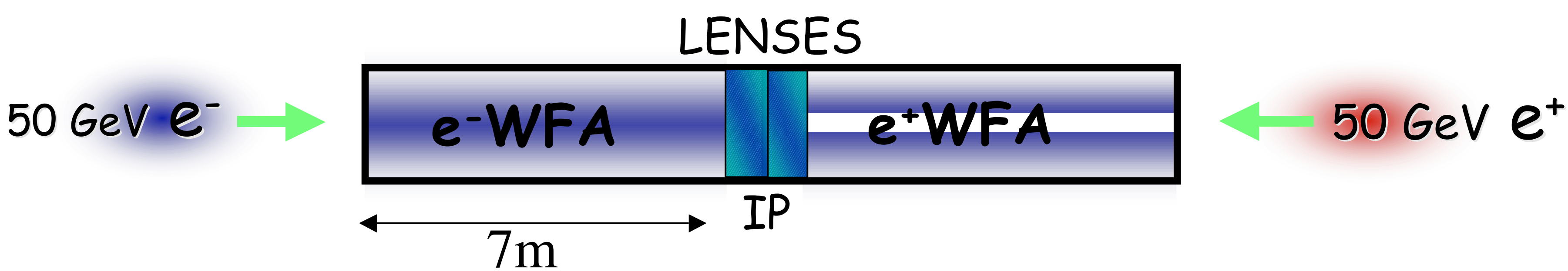
•Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers

•Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma*

•Instabilities may be controlled with n_p>>n_b, and B_z field (Welch, Rose, Kaganovich)

Plasma afterburner for energy doubler

- \- Double the energy of Collider w/ short plasma sections
- before the interaction point.
- \- 1st half of beam excites the wake --decelerates to 0.
- \- 2nd half of beams rides the wake--accelerates to 2 x E_o
- \- Make up for luminosity decrease $\propto N^2/\sigma_z^2$ by halving σ in a
- final plasma lens.



S. Lee *et al.*, PRST-AB (2001)

Physics of Quark - Gluon Plasmas

- **Create high(est) energy density matter**
  - Similar to that existing ~1 msec after the Big Bang.
  - Can study only in the laboratory – relics from Big Bang inaccessible.
  - T ~ 200 - 400 MeV (~ 2-4 x 10^{12} K).
  - U ~ 5 - 15 GeV/fm^3 (~ 10^{30} J/cm^3).
  - R ~ 10 fm, t_{life} ~ 10 fm/c (~3 x 10^{-23} sec).

- **Characterize the hot, dense medium**
  - Expect QCD phase transition to quark gluon plasma.
  - Does medium behave as a plasma? coupling weak or strong?
  - What is the density, temperature, radiation rate, collision frequency, conductivity, opacity, Debye screening length?
  - Probes: passive (radiation) and those created in the collision.

How to get there?

- **Experimental side – upgrade facility (~2009-2015)**
  - Increase RHIC luminosity by ~ 40
  - By electron cooling of heavy ion beams
- **Capabilities of large detectors (2 steps between now and 2015)**
  - Technology for rare features in high muliplicity events
  - Secondary decay vertices
  - Background rejection
  - Triggering, readout capabilities
  - Data analysis infrastructure (already write 0.5 pB/year)
- **Theory progress (over next 5-10 years)**
  - Large scale computing resources
  - Lattice QCD, hydrodynamic & transport simulations
  - Personnel to develop new approaches

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #7 - Materials properties

What are the fundamental properties of matter at extreme states of temperature and/or density?

Thrust Area #8 - Compressible dynamics

How do compressible, nonlinear flows evolve into the turbulent regime?

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #9 - Radiative hydrodynamics

Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

Thrust Area #10 - Inertial confinement fusion

Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

The DOE/NNSA stockpile stewardship facilities are uniquely positioned to address key areas of frontier HED physics

<u>Compelling high energy density physics questions can be addressed by these facilities:</u>

- ***What are the fundamental properties of matter at extreme states of temperature and/or density?***

- ***How do compressible, nonlinear flows evolve into the turbulent regime?***

- ***Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?***

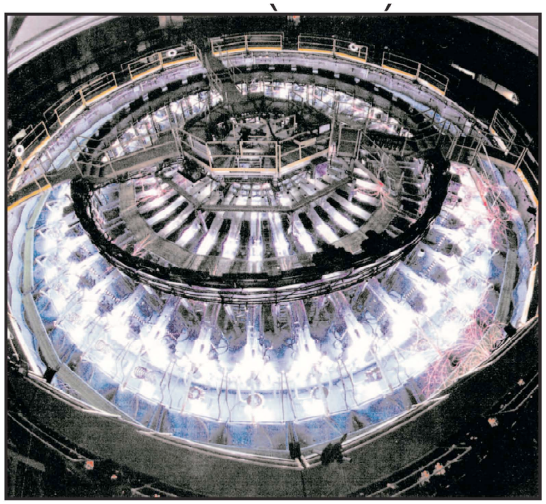
- ***Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?***

The above questions form the basis for four thrust areas:

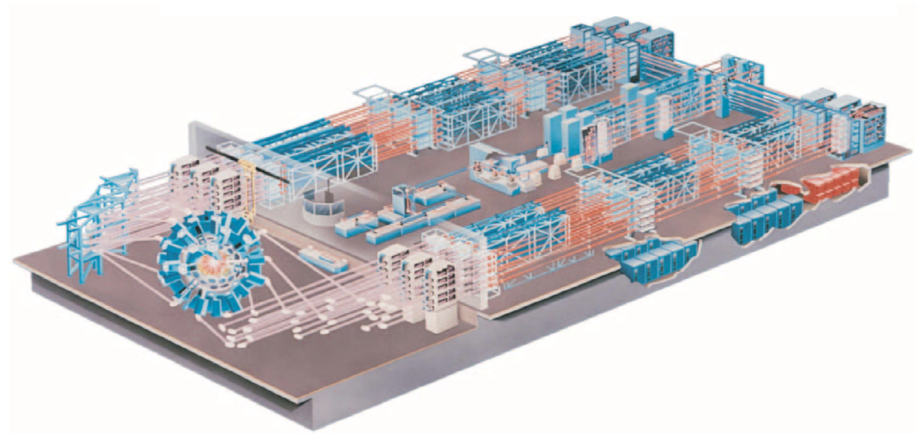
- **Material properties**
- **Compressible dynamics**
- **Radiative hydrodynamics**
- **Inertial confinement fusion**

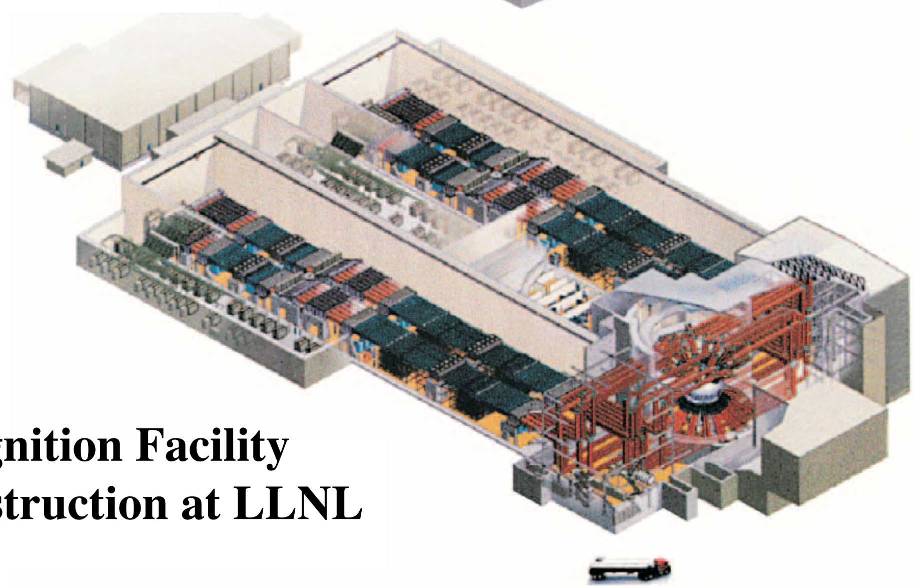
NNSA's high energy density facilities are the core of its inertial confinement fusion ignition program

20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)





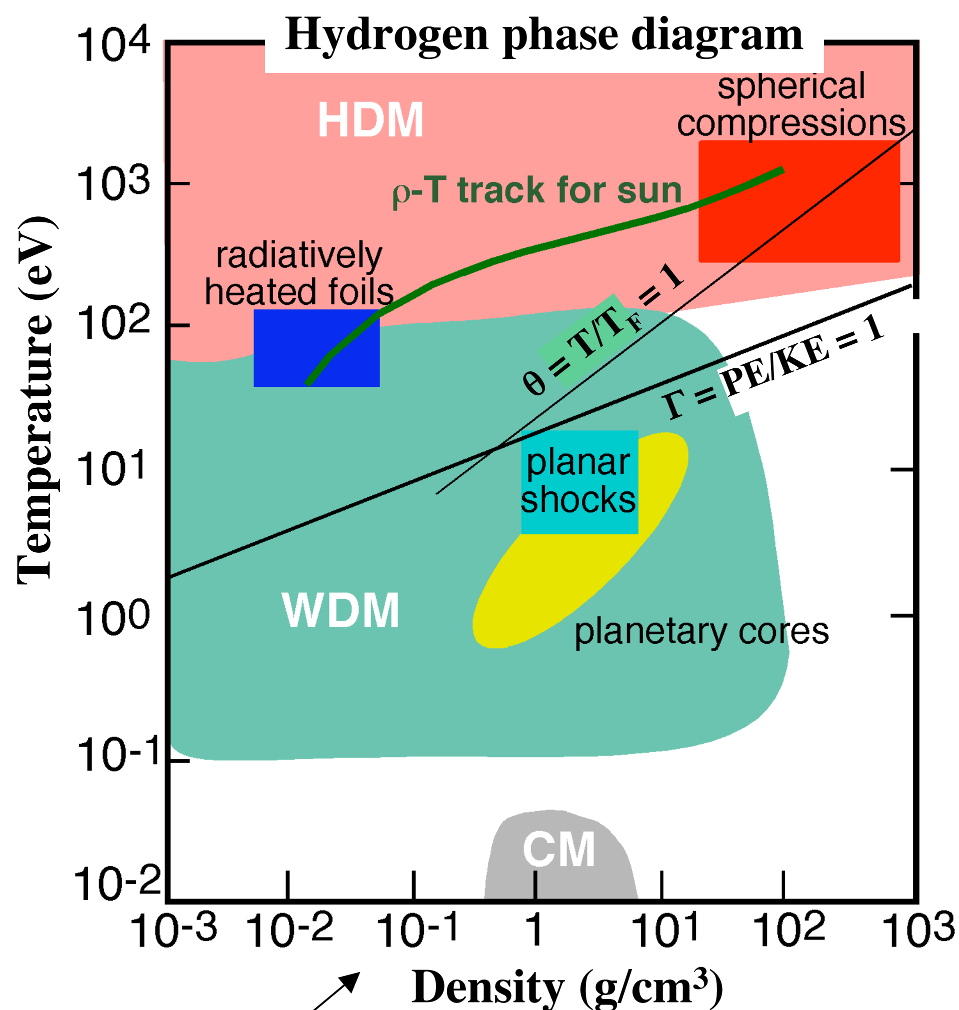
2-MJ National Ignition Facility (NIF) under construction at LLNL

The Material Properties thrust encompasses the study of fundamental properties of matter under extreme states of density and temperature

- **Material Properties describe:**
  - Equation of State (EOS)
  - Radiative opacity
  - Conductivity, viscosity, …
  - Equilibration time

- **Hot Dense Matter (HDM) occurs in:**
  - Stellar interiors, accretion disks
  - Laser plasmas, Z-pinches
  - Radiatively heated foams
  - ICF capsule implosion cores

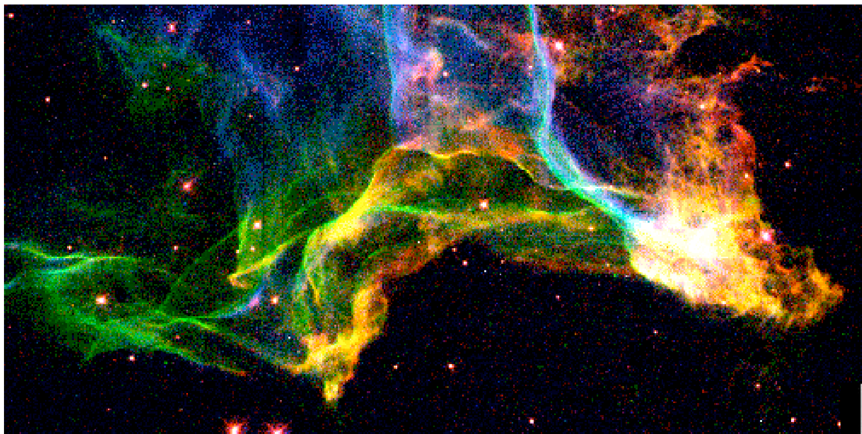
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of giant planets
  - Strongly shocked solids
  - Radiatively heated solid foils



- **Tenuous plasma "easy": Γ = PE/KE << 1;**
- **Dense plasma "difficult": $\Gamma \sim 1$ and $\theta \sim 1$**

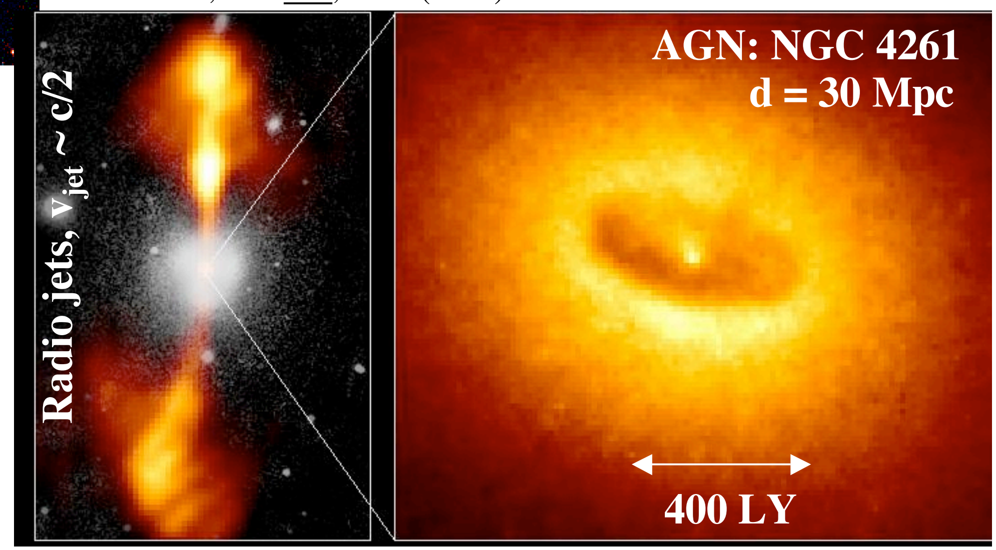
Radiative hydrodynamics abounds in energetic astrophysics

Radiative shocks in the Cygnus Loop supernova remnant (SNR)



Photoionized plasmas in an accreting massive black hole

Piner *et al*., A.J. 122, 2954 (2001)



88,000 LY

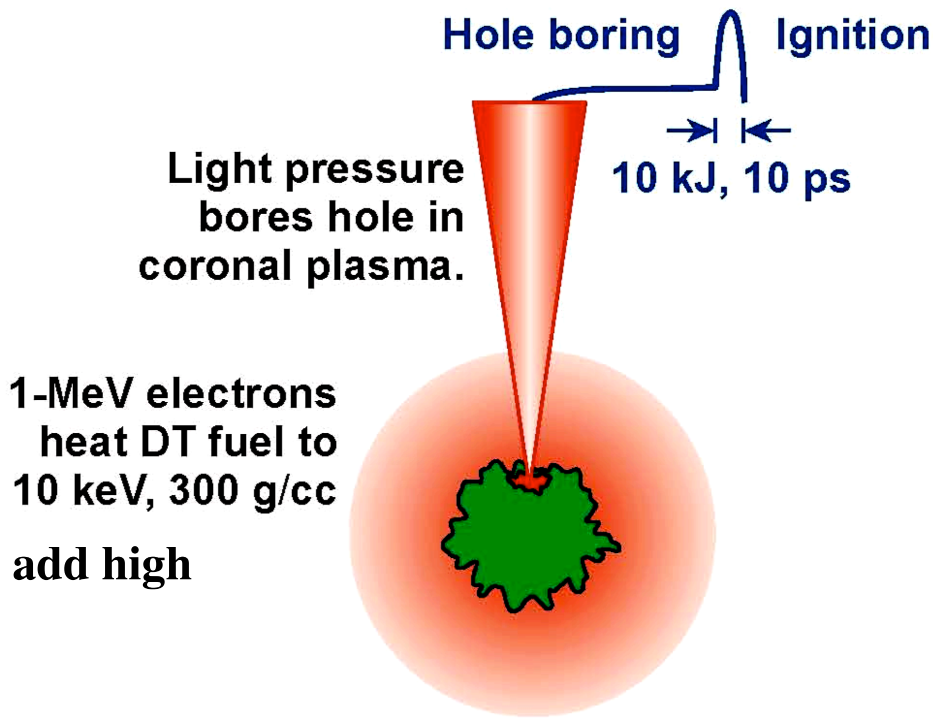
Ferrarese *et al*., Ap. J. 470, 444 (1996)

- **Additional examples of radiative hydrodynamics in astrophysics:**
  - **Radiatively cooled jets**
  - **Radiatively driven molecular clouds**

- **Our understanding of these phenomena would improve significantly if we could develop scaled radiative hydrodynamics experimental testbeds to validate modeling**

Fast Ignition offers the potential to increase target gains and reduce driver energy requirements

- The Fast Ignition concept was proposed in 1994.
- In Fast Ignition, the compression and heating processes are separated.
- Preliminary experiments, including integrated ones in Japan, continue to increase confidence in this concept.
- All three of the large NNSA high energy density facilities are planning to add high energy petawatt capability.
- These combined facilities will address the fundamental question:



Will the Fast Ignition concept lead to higher target gains for the same driver energy?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

Thrust Area #11 - Laser excitation of many-particle systems at the relativistic extreme

How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?

Thrust Area #12 - Attosecond physics

Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #13 - Ultrafast, high-peak-power x-rays

Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of "single" complex bio-molecules that are the constituents of all living things?

Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?

Thrust Area #14 - Compact high energy particle acceleration

How can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeVclass electron and or proton/ion accelerators?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

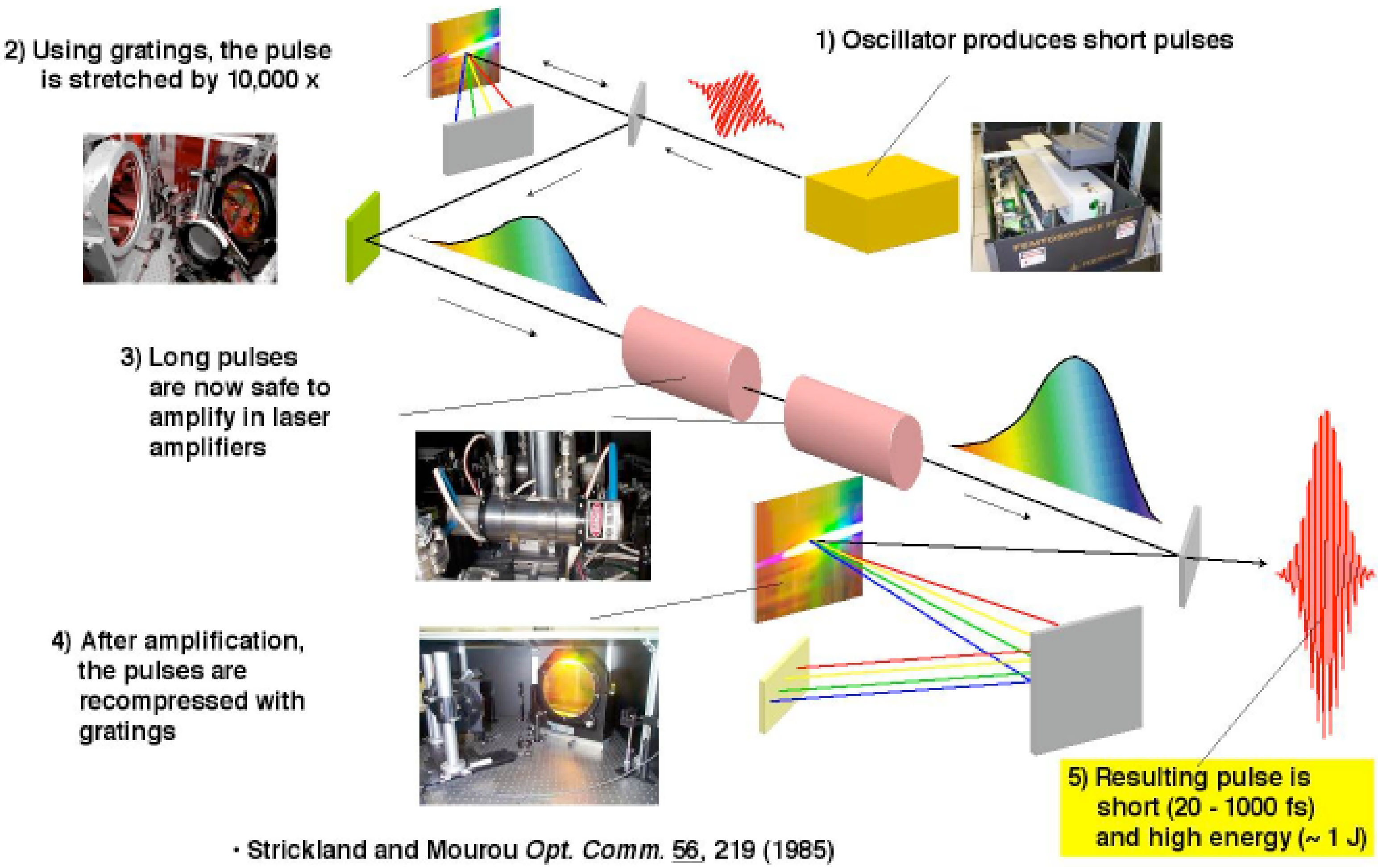
HEDP Task Force

Thrust Area #15 - Inertial fusion energy fast ignition

Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?

The enabling technology for the field of ultrafast ultraintense lasers is chirped pulse amplification

HEDP Task Force



Chirped pulse amplification lasers access extremes in field strength and energy density

HEDP Task Force

Multi-TW laser focused to <10 μm

↓

Focused light intensity of

> 10^{19} - 10^{21} W/cm^2

High Field Science

High electric fields

$E \sim 10^{10} - 10^{11}$ V/cm

Field strength is 10 to 100 times that of the electric field felt by an electron in a hydrogen atom

High electron quiver energy

$U_{osc} = 60$ keV - 3 MeV

Electron motion can become relativistic ($U_{osc} > m_e c^2 = 512$ keV)

High Energy Density Science

Concentrated energy

Energy density in a femtosecond pulse is 10^9 J/cm^3

Corresponds to ~ 10 keV per atom at solid density

High brightness and pressure

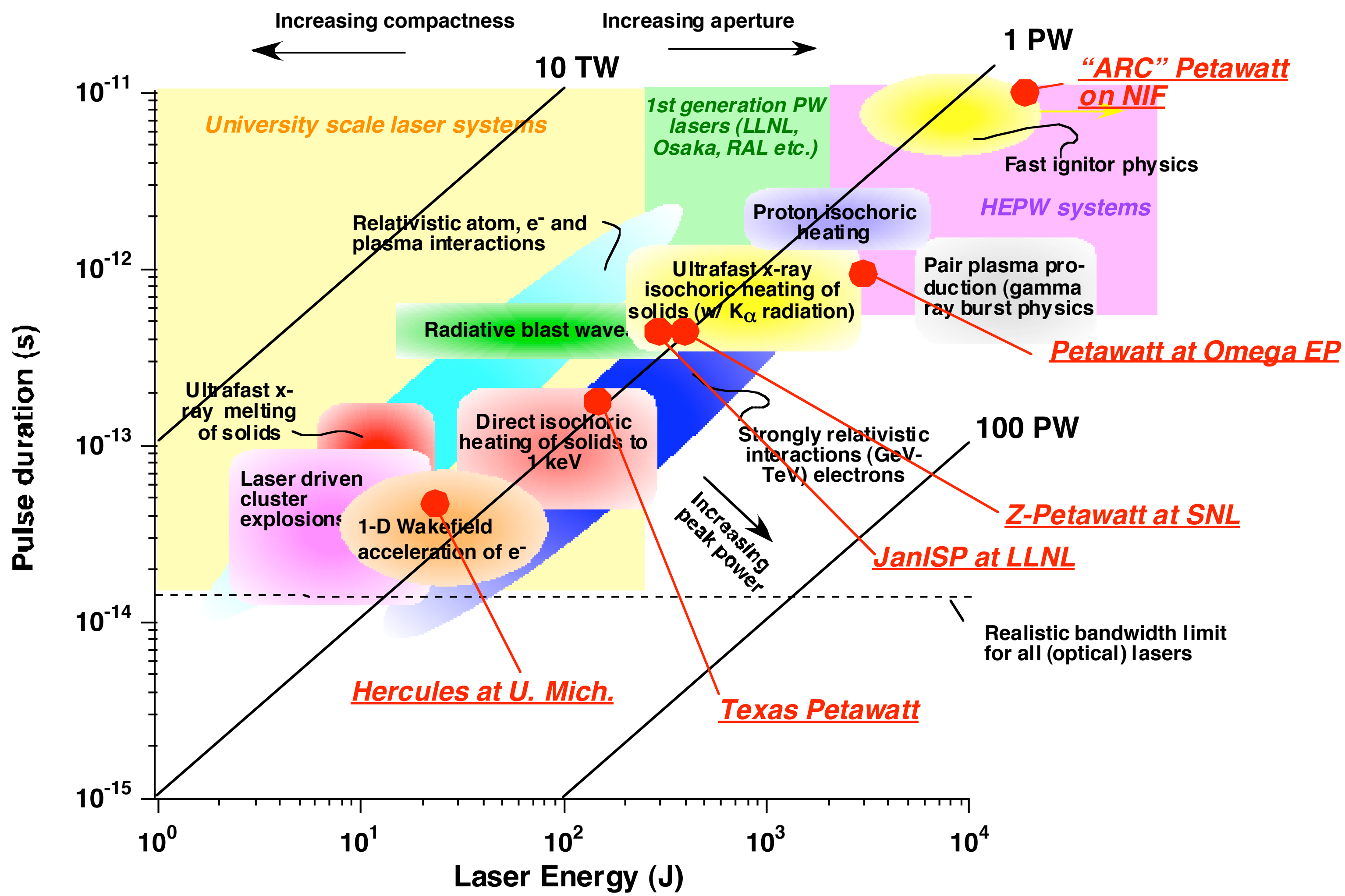
Radiance exceeds that of a 10 keV black body

Light pressure $P = I/c = 0.3 - 30$ Gbar

A variety of different types of Petawatt class lasers are under development, accessing many potential applications

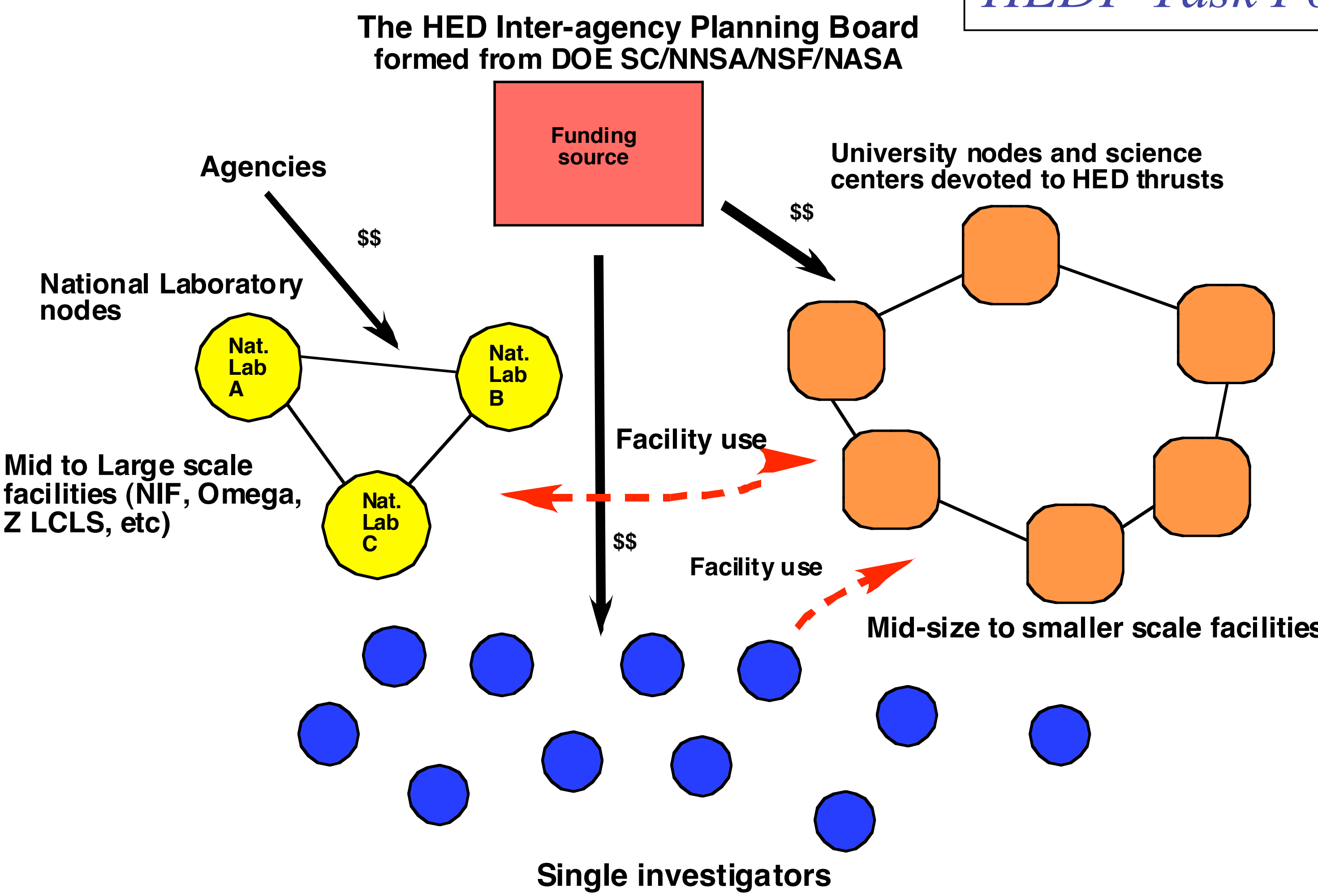
HEDP Task Force

Applications and Petawatt lasers under development in the US



The field of High Energy Density Physics could be propelled with the formation of a national network based around small, intermediate, and large facilities

HEDP Task Force



Five important thrust areas have been identified in ulatrafast ultraintense laser science

HEDP Task Force

- Laser excitation of matter at the relativistic extreme
- Attosecond physics
- Ultrafast, high-peak-power X-rays
- Compact high energy particle acceleration
- Inertial fusion energy fast ignition

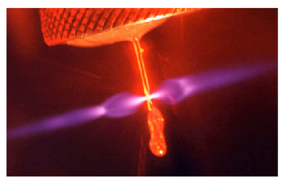
Attosecond Physics

Can physical and chemical processes be controlled with man-made light pulses that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?

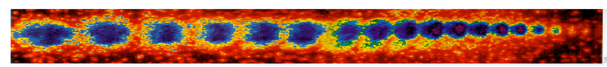
HEDP Task Force

It is now possible to generate XUV pulses shorter than 1 fs

✓ Extreme nonlinear optics
- high harmonic generation



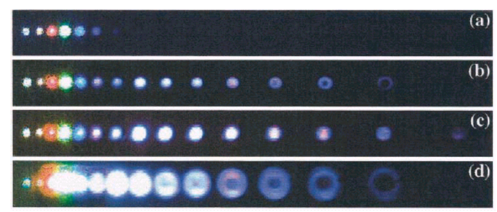
Harmonic orders 27–61



← wavelength (nm)

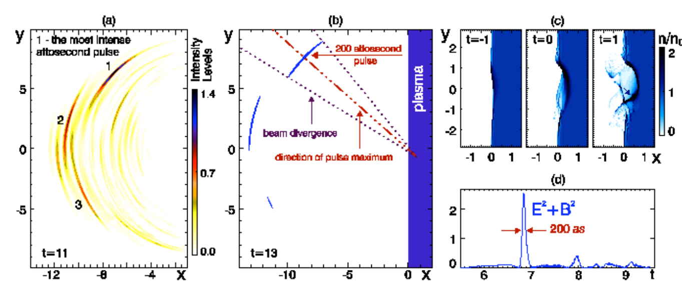
spatial and temporal coherence

- molecular Raman modulation
  S. E. Harris, A. Kaplan

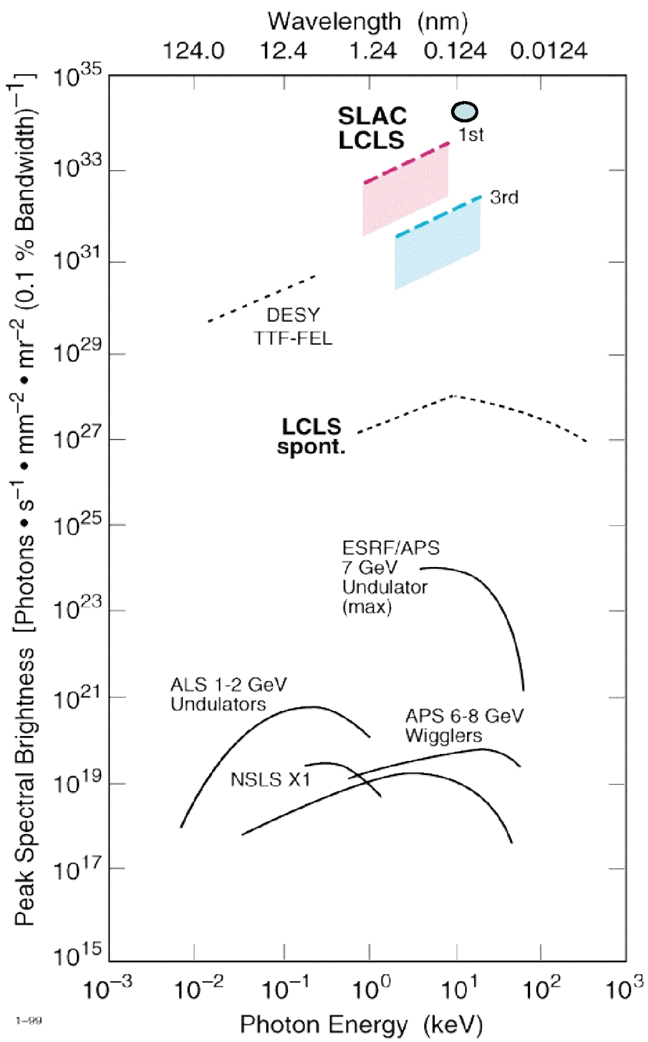


✓ Relativistic plasma wave front

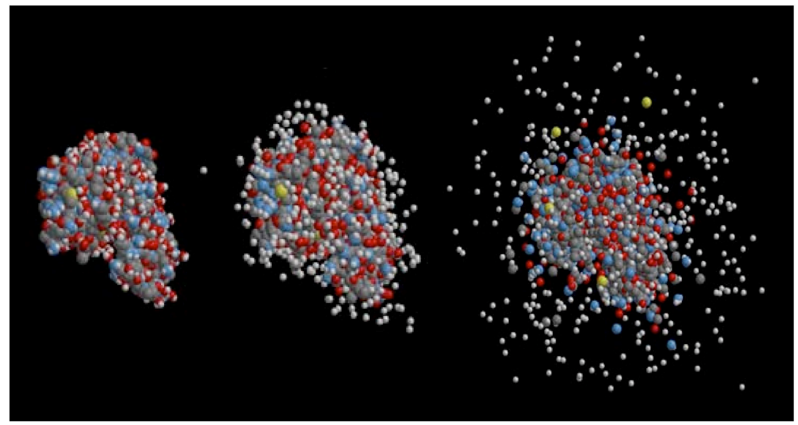
PIC simulations in λ^3 regime
Mourou *et al*., PRL **92**, 063902 (2004).



The Linac Coherent Light Source (LCLS) will revolutionize ultrafast x-ray science

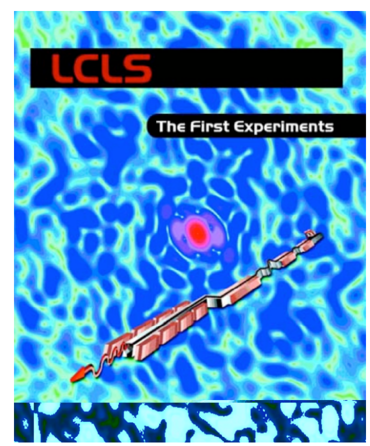


HEDP Task Force



"Potential for biomolecular imaging with femtosecond x-ray pulses"
Neutze R, Hajdu J *et al*., Nature **406**, 752 (2000).

Baseline performance:
- •15-1.5 Angstrom
- •10 GW peak power
  larger by 10^9 to current sources
- •ultra-short, 200 fs - ?
  exceeds 3rd generation by $\geq 10^3$
- •coherent
  large degeneracy factor $\geq 10^9$

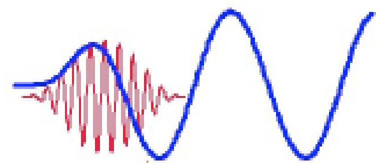


Intense lasers hold the possibility of producing very high acceleration gradients by driving waves in plasmas

HEDP Task Force

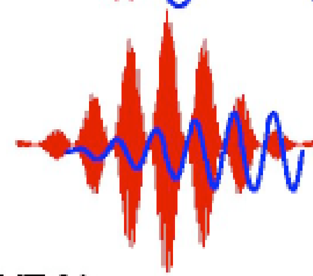
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



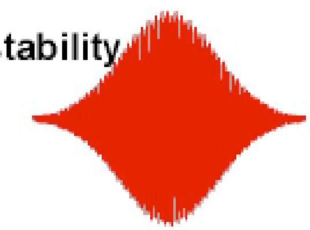
- Plasma Beat Wave Accelerator(PBWA)

  Two-frequencies, i.e., a train of pulses

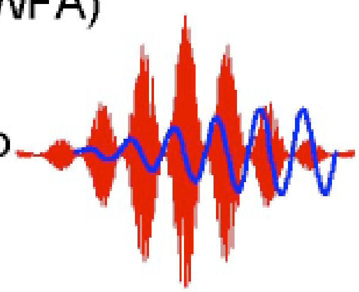


- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability



evolves to



- **The radiation pressure, 100 Gbar, expels plasma electrons which are then attracted back by the more massive ions. This creates a high gradient wake, eE~[n_o (cm-3)]$^{1/2}$ V/cm. This can easily exceed 100 GeV/m (SLAC is 20 MeV/m).**

- **Energy density of plasma wave, ~10^6J/cm^3.**

Map of the High Energy Density Physics Universe